



**An Input to the
UVOIR Panel
Of the AASC**

April 1, 1999

“Whatever you do in astronomy, you need to know distances to what you study. Precise distances enable fundamental science that is otherwise impossible. This is the reason the Decade Survey placed such a high priority on the development of a space interferometric mission.

An improvement of a factor of 10 in instrumental sensitivity or precision often leads to major discoveries in astronomy. A thousandfold improvement in precision is extremely rare and, if recent astronomical history is any guide, seems almost certain to lead to revolutionary discoveries.

This book provides a clear and simple statement of how SIM will work and what will be some of the major arenas for the scientific studies. Just glance at the topics listed; there is almost certainly something close to your own personal wish list. Here are just a few that make my mouth water: calibrating stellar evolutionary theory by measuring precisely the distances to stars of many different types with accurately known masses, luminosities, and pulsation characteristics; measure the masses to better than 1% of stars in binary systems; determining the size, the rotation rate, and the mass distribution of the Galaxy; establishing direct distance measurements to nearby spiral galaxies independent of all intermediate distance indicators; and measuring the peculiar velocities of nearby galaxies that reflect the initial perturbation spectrum and the distribution of mass, dark and visual, in our own neighborhood.”

*An excerpt from the preface written by
John Bahcall for the SIM book*

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Background

Tracing SIM to the Bahcall Report

The foundation of the Space Interferometry Mission (SIM) science objectives is firmly rooted in the recommendations of the last Astronomy and Astrophysics Survey Committee (1991 Bahcall Report). The report recommended an astrometric interferometry mission as a high priority for the 1990s possessing the following attributes (from page 85 of the report):

“The mission requirement would be to measure positions of widely-separated objects to a visual magnitude of 20 with a precision of 30 millionths of an arcsecond; a more challenging goal would be to measure the positions with a precision of 3 millionths of an arcsecond.”

SIM’s requirement is to perform global astrometry at the level of 4 millionths of an arcsecond — which is at the most stringent end of the recommended range.

“The [mission] . . . would permit definite searches for planets around stars as far away as 500 light years through the wobbles of the parent star . . .”

SIM’s requirement is to perform narrow-angle astrometry at the level of 1 μ as, which permits detection of Jupiter-mass planets many thousands of light years away, and planets with masses as small as a few Earths around nearby stars.

“[The mission would permit] . . . trigonometric determination of distances throughout the [G]alaxy . . .”

SIM will be able to directly measure distances via parallax to better than 10 percent anywhere in the Galaxy. Furthermore, SIM will put the cosmic distance scale on solid footing by directly calibrating the luminosity of Cepheids.

Beyond the Bahcall Recommended Science

The Bahcall Report, referring to its recommended astrometric interferometry mission, noted that

“[The mission] . . . would demonstrate technology required for future space [interferometry] missions.”

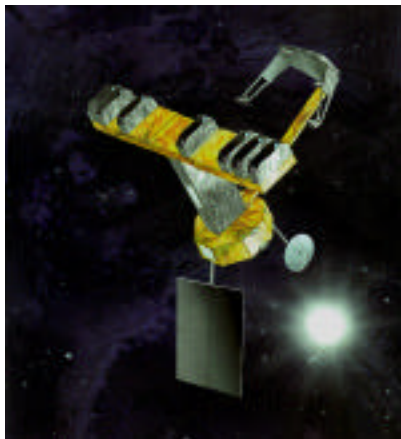
In March 1996 NASA held a review to select between two competing architectures to ensure that the design selected for SIM would pave the technological path toward future interferometers, including the Terrestrial Planet Finder (TPF). The architecture selected from that review is the basis for the designs being considered for SIM.

Many of the technologies needed to accomplish SIM’s astrometric science (such as nanometer-level optical pathlength control, space-rated picometer laser metrology, and autonomous operation of space-based interferometers) are also needed for TPF. These technologies are needed

for SIM astrometric science; synthesis imaging and starlight nulling are capabilities which SIM will demonstrate as a precursor to TPF.

Designs under Study

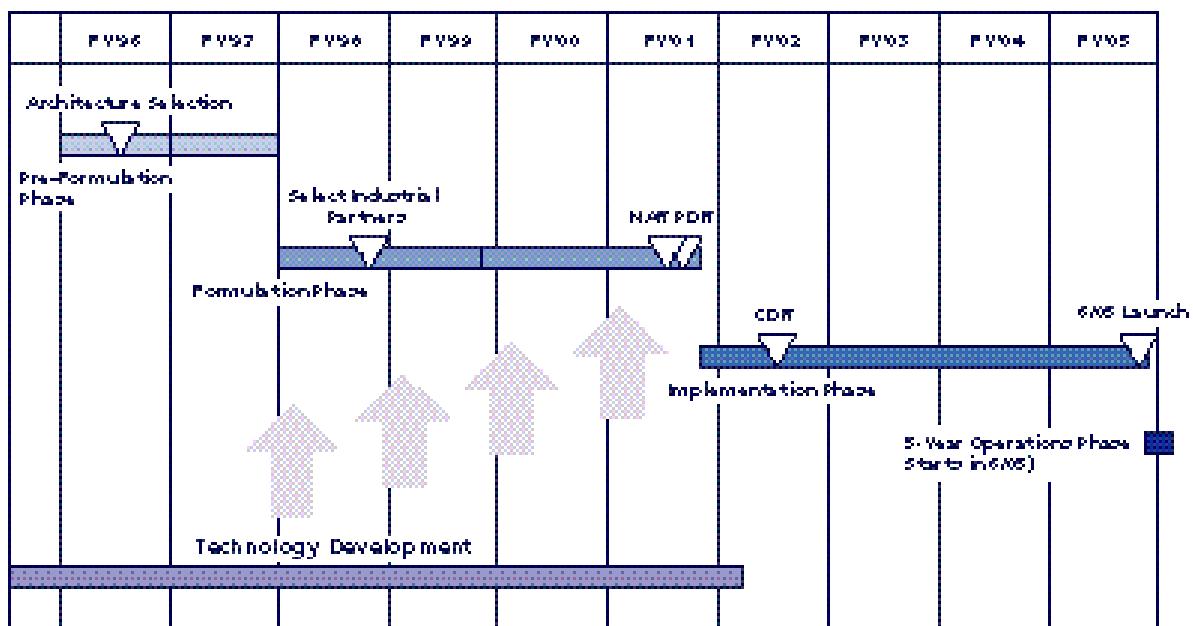
Two designs are currently under study for SIM. Within the SIM team, these have come to be known as “SIM Classic” (or simply the Classic) and the “Son of SIM” (SOS). While the two designs require many common technologies, each design also presents a set of unique technological challenges with the promise to reduce implementation and/or operational difficulties and risks in different areas. The choice between the two will be made before the fall of 1999, based on the results and progress of the technology development program and cost/complexity design trades.



SIM Classic



Son of SIM



SIM Synoptic Schedule

Question 1: What are the primary astronomical problems that the mission will address?

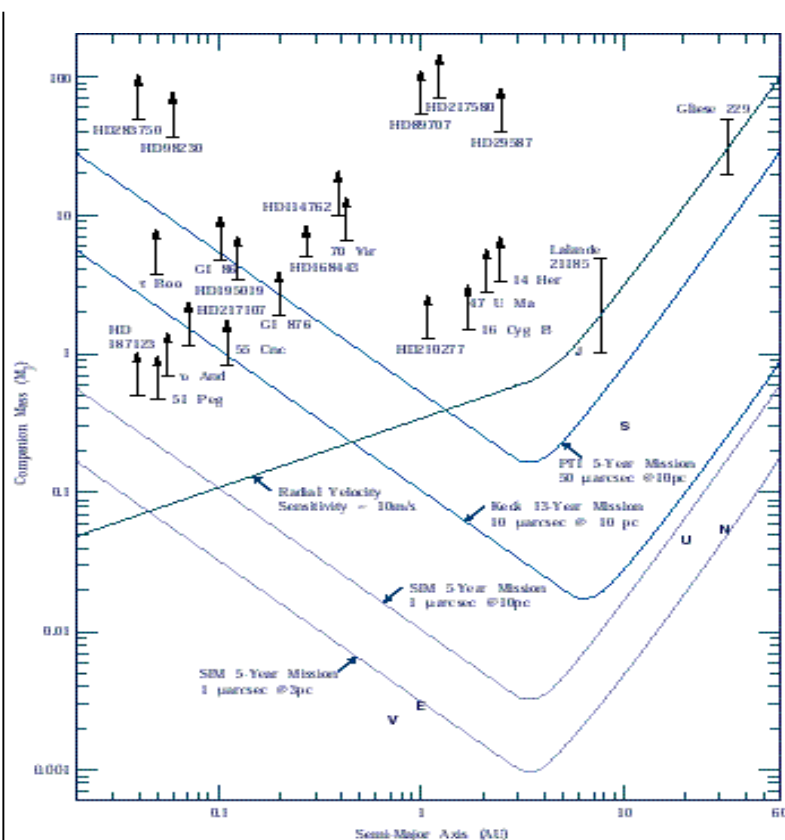
SIM offers an improvement of a factor of about 250 in astrometric accuracy over existing instruments. It will provide the observational data needed to answer a wide range of problems in astrophysics. We have selected three topics to illustrate the potential of microarcsecond astrometry:

1. The detection of extrasolar planets down to a few Earth-mass and quantitative characterization of planetary systems
2. Setting the cosmic distance scale on a firm foundation, by direct precision measurement of distances to fundamental distance indicators
3. Astrophysics of stars of a wide range of classifications, through precision measurements of mass and distance.

Topic 1: The Detection and Characterization of Extrasolar Planetary Systems

Extrasolar planets are a reality. In the last few years, the first planets outside the solar system have been discovered, using radial-velocity techniques capable of finding massive, Jupiter-like planets. However, SIM will step far beyond existing detection techniques, allowing planets hundreds of times smaller in mass to be discovered. This means that for the first time in human history, we will be able to discover whether or not our neighboring stars have planets approaching Earth's mass.

Searching for planets is a quest that is certain to yield important, and exciting results. Our understanding of planetary systems—both theoretically, and observationally—is still in its infancy. But the prospects for a much more complete census of the local stellar neighborhood, together with improved physical models of the formation process, ensure this will be a fruitful area of



Discovery space for SIM astrometry and other techniques is shown above. The masses and semi-major axes are shown for recently discovered substellar objects. Earth, Venus, Jupiter, Saturn, Uranus, and Neptune are shown by their first letter. The diagonal lines give the limiting accuracies of current astrometric and radial-velocity surveys. SIM's accuracy is shown for stars at 3 and 10 pc.

astronomical research for decades to come. This quest resonates strongly with the public interest in astronomy, because it seeks, ultimately, to answer the age-old question, 'Are we alone?' SIM will be only the first in a sequence of space instruments designed to study extrasolar planets, but it will be the most important step in the next decade towards understanding planetary systems.

A Census of Planetary Systems. The defining capability of SIM for extrasolar planets will be its ability to measure with unprecedented accuracy the center-of-mass motions of nearby stars and to follow those movements for the duration of the five-year mission. The design accuracy is **1 μ as** in a single measurement for astrometry in a narrow-angle field. This is numerically equal to the reflex motion of a solar mass star with an Earth-mass companion in an orbit of 1 AU observed from a distance of 3 parsecs. Of the planet detection methods available, only SIM will detect or rule out the presence of large terrestrial planets, determining their statistical occurrence.

SIM's accuracy will allow it to probe a range of planet masses and orbit radii which is inaccessible by other methods. SIM will derive astrometric orbits for all but two of the currently known radial-velocity companions with substellar minimum masses. Radial velocity methods have revealed what is likely to be a large population of planets with masses upward of around 1 Mj. However, these masses are all lower limits, because the orbit inclination cannot be measured by the radial velocity method. Since SIM will measure the transverse components of the velocity signature, the orbit inclination, and hence the planet mass, will be *directly measurable*.

Proposed astrometric survey missions will cover many more stars than SIM, but they will lack the astrometric accuracy to make a significant contribution to the overall census of planetary systems, especially at the low-mass end.

Understanding Planet Formation. Planetary mass is an indicator of the planetary formation process — the endpoint of the star formation. SIM will play a key role in developing our understanding of these processes, by direct measurement of planetary masses. We expect a low-mass cutoff for brown dwarfs associated with the fragmentation process, and for planets, an upper mass cutoff related to the limited density of protoplanetary disks. Neither of these mass cutoffs is well understood, and brown dwarfs and planets may populate a common mass range, probably 1 to 10 Jupiter masses. Already, radial velocity studies have indicated an apparent deficit of planets in roughly this mass range.

Empirically, applying mass as a discriminator between planets and brown dwarfs is currently hampered by two factors: mass uncertainty for the radial-velocity discoveries (due to ambiguity in the inclination angle), and incompleteness in the mass range corresponding to Solar System planets (due to inadequate sensitivity). SIM will remove these impediments by directly measuring masses of planets in this critical mass range.

Planetary Orbits. Another issue in the understanding of planetary systems is the shape and alignment of the companion orbits. Orbital eccentricity is expected to have a broad distribution for brown dwarfs, as is found for binary stars, but small values are expected for planets due to averaging effects as planets are built up from large numbers of smaller planetary embryos.

SIM will be a powerful instrument for determining orbital parameters, since a complete set of observations yields all six Keplerian elements. As it is a pointed instrument, SIM can be scheduled flexibly, allowing more detailed study of most interesting systems. Known single-planet systems are obvious candidates for such a search—a search that would probe with 100 to 1000 times more sensitivity, down to a few Earth masses.

Coplanar orbits are expected for multiple-planet systems, as a remnant feature of the flat protoplanetary disk, whereas brown dwarfs should mimic multiple star systems, which often do not have coplanar orbits. Hence orbital shape and coplanarity are valuable discriminators between models. SIM will directly measure the orbit parameters of multiple systems. The scope for surprises is large. We have empirical models to explain the basic facts about the Solar System—based on an initial collisional phase followed by gas accretion phase—but they have yet to be tested on an ensemble of planetary systems. SIM will provide crucial insight about the mechanisms of planet formation by detecting planets in the range of 2 to 20 Earth masses around a large sample of nearby stars—it is in this mass range where we expect to find the key diagnostic of the two-step formation process.

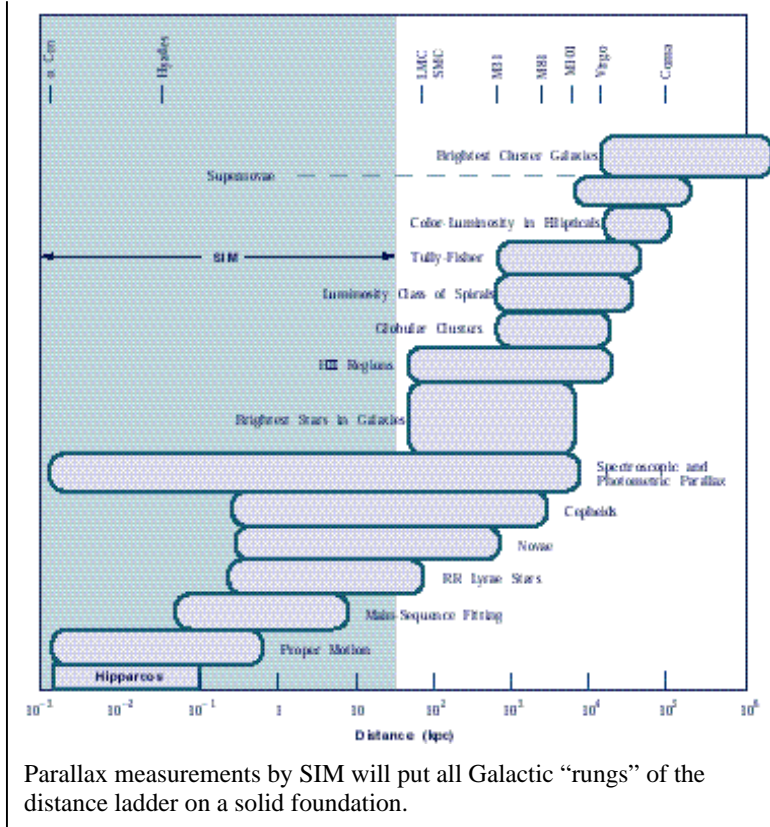
Topic 2: SIM's Contribution to Cosmology

How big is the universe? How fast is it expanding? How old is it? How is its mass distributed on a large scale? The answers to these fundamental questions in cosmology rely on accurate distance measurements to galaxies far enough away that their velocities are determined mainly by the Hubble flow. These measurements, in turn, depend on accurate calibrations of standard candles or standard rulers in those galaxies. Currently these calibrations are only known to 10 percent, while the fundamental observables of galaxies, i.e., redshifts and apparent brightnesses of constituents, are known to much higher fidelity. Differences in interpreting cosmological models reside within that 10 percent uncertainty.

Calibrating the Cepheids.

Distances to Galactic Cepheids represent the first step of the extragalactic distance scale. Uncertainties here propagate outward, limiting the potential accuracies of distance measurements at cosmological distances. SIM will contribute to a major advance in the extragalactic distance scale for the same reason — SIM will measure parallaxes to an accuracy of **4 μ as**. This will take the Galactic Cepheid calibration from the current 10 percent level to below 1 percent, and will similarly improve the accuracy of all subsequent steps in the distance scale. A secure foundation on the kiloparsec scale will provide the motivation for further improvement of distance indicators for larger scales.

Parallax distances are completely unambiguous and



with typical distances of 1-4 kiloparsecs for Galactic Cepheids, SIM will determine their distances to 1 percent. For the first time, a Cepheid period-absolute magnitude diagram will be available which is limited not by uncertainties in the distances, but by such issues as uncertainty in extinction corrections to the absolute magnitudes. Accurate near-infrared photometry minimizes extinction's effects; thus one can expect to make progress on the question of whether the period-absolute magnitude relation is dependent on other parameters such as metallicity. Such parameters, when taken into account, can further improve use of Galactic Cepheids as distance indicators.

SIM's ability to make precise astrometric observations will help in developing our physical understanding of these stars. There are a small number of Cepheid primaries in double star systems. By mapping out their orbits, the masses of the two stars will be determined by applying Kepler's laws. Masses accurate to 1%, combined with similarly accurate luminosities and metallicities, as well as their much more accurately known periods, will lead to a detailed physical understanding and application of Cepheid models as a tool in improving their use as distance calibrators.

Rotational Parallaxes to Nearby Galaxies. With a Galactic Cepheid distance calibration in hand, how will we know that it is in fact applicable to external galaxies? Once again, a SIM experiment will tell us the answer, this time by using the technique of rotational parallaxes to find the distances to the nearest galaxies. This method is similar to how the distances of binary stars are found from their astrometric orbits and kinematic data describing their radial velocities. SIM will observe the proper motions of individual stars in the rotating disk of a galaxy like M31. By combining their proper motions, which are as large as $100 \mu\text{as/yr}$ for M31, with radial velocities accurate to a few several km/s, an ensemble of such observations leads to a distance estimate accurate to a few percent. Comparing this rotational parallax distance with a Cepheid distance to M31 serves as a check on the Cepheid distance scale.

Topic 3: Precision Stellar Astrophysics

SIM will lead us into an era when stellar properties are known at the level of 1 percent, enabling very detailed investigations into the physics of stars and groups of stars. Measuring fundamental stellar properties requires accurate distances. SIM's parallax measurements will be accurate to $4 \mu\text{as}$, improving 250-fold upon those of Hipparcos, vastly expanding the volume over which accurate parallaxes are known, and hence also the variety of stars with accurate distances. The ability to observe as faint as $V = 20$ ensures that astrometry of these stars can be performed, even at these great distances. Most properties of stars are currently known to a typical precision of 10 percent, or even worse, limited mainly by uncertainties in distance. Except for the Hipparcos parallaxes of the nearest stars, those within a few tens of parsecs, available direct parallax distances are of low accuracy. SIM-derived precise properties of stars coupled with theoretical investigations of stellar evolution will advance our understanding of the detailed physics of stellar interiors.

Stellar Mass Determinations. Since the time of Eddington, we have understood that mass is the fundamental stellar parameter. No means has yet been found to determine reliable stellar masses other than through dynamical interactions. Precision astrometry with SIM will yield stellar masses with better than 2%-uncertainties for binary stars within 500 pc, sampling even the most massive stellar types, which are present in the Orion OB association.

Binary Star Evolution. The evolution of close binary stars can be very different from that of wide binaries of isolated stars. If the stars are close enough, mass is exchanged as first one star, then

the other, evolves off the main sequence. In some cases the mass exchange leads to a supernova explosion and the formation of a compact object. Understanding the details of these processes requires accurate knowledge of the initial masses and evolutionary tracks of the stars. Masses derived by SIM will specify a point in parameter space that any model of the system under consideration must satisfy.

Knowledge of masses for non-interacting binaries, where the evolution of each star is independent, is important for checking and calibrating standard stellar evolution theory against a number of parameters. Mass is the key parameter, but also important are chemical composition, rotation, the physics of mass-loss and internal mixing, and of course, the stellar age.

Low Mass Stellar Evolution. We have discussed briefly the most massive stars, but SIM will also lead to an improved understanding of the least massive stars, in particular to an understanding of the hydrogen-burning limit, below which stars fail to sustain nuclear reactions in their centers. This limit is somewhere around 0.08 solar masses, based on current models. SIM allows an empirical approach by observing low mass stars and brown dwarfs in binaries, where the nearest have masses that can be determined to a few tenths of a percent. One relatively close system is GD 168B, discovered by Becklin and Zuckerman. It has a low mass object near the hydrogen-burning limit in a 120-AU orbit around a white dwarf primary. SIM masses for these stars will be accurate to 0.1%.

Astroseismology. Even with one solar mass main sequence stars, an extraordinary advance is potentially in the making. Helioseismology has shown the remarkable detail to which solar type stars can be analyzed. There is now the expectation that shortly a high precision photometric satellite will be launched, capable of characterizing the acoustic modes of nearby AFG dwarfs. The potential return includes a direct measurement of individual ages through the observed Hydrogen/Helium profiles in the cores. Luminosity is a fundamental parameter of the stellar models. Luminosity determination requires accurate distances. SIM will provide parallax distances at the required 0.3 % precision out to 750 pc. At present, Hipparcos parallaxes provide this precision only for a single star, Cen.

Other SIM Science

SIM will contribute profoundly to a number of other areas of astrophysical inquiry. Below we outline a selection of those topics which were not covered above:

Ages of Globular Clusters: The primary uncertainty in the derived ages is the distance determination. SIM will reduce the uncertainties by a factor of two, sharpening the confrontation with the expansion age of the universe.

Microlensing with Nearby Brown Dwarfs: By observing faint, high velocity, nearby objects that will pass within about an arcsecond of some bright ($V < 20$) background star, SIM will measure masses of field brown dwarf candidates.

Dynamics and Structure of the Milky Way: SIM's astrometric capabilities are an excellent match to the kinematics of the Galaxy. Coupled with radial velocity measures SIM will map out the full six-dimensional phase space of the system. Many long-standing questions in the area of Galactic structure will be resolved.

Dynamics of the Local Universe: SIM will measure the proper motions of any system with a significant Population I component within 3-4 Mpc of the Galaxy. Combined with radial

velocities, a complete kinematic picture of the local universe will be developed, enabling detailed comparisons with Local Group dynamical models.

Question 2: What are the performance specifications of the mission, and how do they address these astronomical problems?

Mission Performance Specification

The Space Interferometry Mission is a space-based 10-m baseline optical Michelson Interferometer. In its wide-angle mode, SIM will be capable of providing 4 μs precision absolute position measurements of stars, with parallaxes to comparable accuracy, at the end of a 5-year mission. The expected proper motion accuracy is around 2 $\mu\text{s}/\text{yr}$, corresponding to a transverse velocity of 10 m/s at a distance of 1 kpc. In its narrow angle mode (1 μs accuracy), SIM will search for planetary companions to nearby stars, by detecting their astrometric 'wobble'.

SIM Instrument and Mission Parameters

| | |
|-----------------------------|----------------------------------|
| Baseline | 10 m |
| Wavelength Range | 0.4 – 0.9 μm |
| Telescope Aperture | 0.3 m diameter |
| Astrometric Field of Regard | 15° (Wide Angle) |
| Astrometric Field of Regard | 1° (Narrow Angle) |
| Imaging Field of View | 0.3 arcsec |
| Orbit | Heliocentric Earth-trailing |
| Mission Life | 5 years (launch Mid-2005) |
| Wide Angle Accuracy | 4 μs (End of Mission) |
| Astrometry Sensitivity | 20 mag in 4 hours |
| Narrow Angle Accuracy | 1 μs |
| Imaging Resolution | 10 milliarcsec |
| Imaging Sensitivity | 20 mag in 1 hour (point source) |
| Interferometric Nulling | Null depth 10^{-4} |

Within each "tile" of a 15-degree wide field of regard, SIM will take multiple relative measurements of the separations of "Grid Stars". Wide-angle astrometry is performed by combining the relative positions of the grid stars in overlapping tiles and constructing an astrometric grid, covering the entire sky.

Capability for Planet Detection

The defining capability of SIM for extrasolar planets will be its ability to measure the movements of nearby stars with unprecedented accuracy for the duration of the five-year mission.

The design accuracy of 1 μs (in a single measurement for astrometry in a narrow-angle field) is numerically equal to the orbital semi-major axis of a Sun-mass star with an Earth-mass companion in an orbit of 1 Astronomical Unit (AU) observed from a distance of 3 parsecs. This accuracy— sufficient to measure the displacement of a stellar photocenter by one-thousandth of a solar diameter at 10 pc — is nearly a thousand-fold improvement over current astrometric practice.

Capability for Distance Scale Calibration

Distances to Galactic Cepheids represent the first step of the extragalactic distance scale, made possible by SIM's wide astrometric mode of operation. Uncertainties here propagate outward, limiting the potential accuracies of distance measurements at cosmological distances.

Parallax distances are completely unambiguous, and with typical distances of 1-4 kpc for Galactic Cepheids, SIM will determine their distances to 1 percent. For the first time, a Cepheid period-absolute magnitude diagram will be available, limited not by uncertainties in the distances, but by such issues as uncertainty in extinction corrections to the absolute magnitudes. Accurate near-infrared photometry minimizes extinction's effects, and with distances no longer a problem, one can expect to make progress on the question of whether the period-absolute magnitude relation is dependent on other parameters such as metallicity, which when taken into account can further refine their use as distance calibrators.

A direct measurement of the distance to two or more nearby spiral galaxies has the advantage of both adding to the local Cepheid calibration and providing a direct zero point for the Tully - Fisher relation. The latter is currently the main method of establishing the Hubble constant and of calibrating Supernovae as standard candles for evaluating the acceleration parameter. These are two of the three critical parameters (along with the "cosmological constant") believed to characterize our Universe. Proper motions of objects fainter than $V=16$ and accurate to the order of $2 \mu\text{as/yr}$ enable the distances determinations to M31 and M33.

Capability for Challenging Stellar Astrophysics

Measuring fundamental stellar properties requires accurate distances. SIM will yield very precise data on nearby stars, extending the distance and hence the variety of stellar types, for which 1-percent measurements are available. Most properties of stars are currently known to at best a precision of a few percent, and more typically ten percent or worse, limited mainly by uncertainties in distance. Direct parallax distances are of low accuracy except for Hipparcos parallaxes of the nearest stars. SIM's parallax measurements will be accurate to $4 \mu\text{as}$, improving 250-fold upon Hipparcos. Coupling SIM-derived fundamental properties of stars to theoretical investigations of stellar evolution will drive our understanding of the detailed physics operating in the interiors of stars.

Question 3: What are the key decision-nodes and trade-offs in defining those specifications?

There are three critical specifications that effectively define the mission scientific capabilities: a wide angle mission accuracy for positions of $4 \mu\text{as}$ (from which follows a similar accuracy for parallaxes and a $2 \mu\text{as/yr}$ for proper motions), a narrow angle single measurement accuracy of $1 \mu\text{as}$ and a limiting magnitude of $V=20$. Additional requirements for imaging and response time for targets of opportunity are discussed below.

Wide Angle Astrometry

The wide angle specification matches that needed to measure the Galaxy. Objects at $2R_{\odot}$ on the other side of the Galactic center ($d=25 \text{ kpc}$) will have distances accurate to 10%. In part, the $V=20$ specification is to assure that some objects are detectable at that distance through some reddening. Galactic studies will be limited by parallax accuracies unless other constraints can be applied, and not by the accuracies of the proper motions.

This specification prevents us from measuring parallactic distances to Galaxy satellites, notably the Magellanic Clouds to $<5\%$. The prospect of measuring distances to the Clouds and other galaxies in the local group rests with dynamical techniques. Using the angular motions of a few

nearby spirals (notably M31 and M33) it should be possible to derive distances kinematically, perhaps to 5% or better. Alternatively, orbits of double stars in those galaxies need to be measured.

Limiting magnitude of $V=20$. SIM's sensitivity limit of $V=20$ is driven by three key experiments on faint objects. Understanding the internal dynamics and orbital motions of globular clusters and small distant satellite galaxies of the Milky Way requires observing the $V=20$ Population II stars in these systems. Astrometric determinations of MACHO lens masses requires observing typically $V=20$ lensing events while in progress. Finally, determining the distances to nearby galaxies via rotational parallax requires going down to $V=20$ for systems, such as M-106 and NGC-7793.

Narrow Angle Astrometry

One of the key science goals of SIM is the detection of Earth-mass planets around nearest stars. This goal requires 1 μ as accuracy for narrow angle astrometric observations. For comparison, the signature of the Earth-induced reflex motion of the Sun as seen from Cen is 4 μ as. This capability allows SIM to explore the population of planets from "massive" terrestrial planets (~ 3 Earth masses) up to Jupiters and on into the brown dwarf population. This technique derives actual masses (strictly, planet-to-star mass ratios with no inclination uncertainty).

Imaging and Nulling

SIM will provide a range of baseline lengths for aperture synthesis imaging (and will rotate about the line of sight to fill in the UV -plane). This capability, when combined with a capability for nulling to a depth of 10^{-4} , will enable a number of interesting imaging investigations. We describe two very briefly.

Circumstellar Dust Disks. SIM will image reflected light off dust disks around a number of stars to well within one AU radius, using nulling mode. This will complement the IR measures expected from SIRTf and will allow investigation of spatial structure at high resolution. This further assists with planning for TPF and advances our understanding of the planet formation process from an entirely different perspective.

Kinematics of Emission-line Gas in Nearby AGN. The combination of good UV -plane coverage and accurate visibility calibration enables SIM to make high dynamic range images of many targets. Using the low resolution ($R \sim 100$) spectral dispersion (required for astrometric operation of the interferometer) it will be possible to image a nearby AGN in H- emission, and hence analyze the gas kinematics to within 10 milliarcsecond of the center of the AGN. This will substantially improve the minimum mass density determination for the putative black holes present in the nuclei.

Both of these objectives can be achieved with a range of baseline lengths between 1 meter and 10 meter, which can be accommodated in both of the SIM designs now under study.

Targets of Opportunity

The specification is a 4-day maximum wait to change the scheduled instrument pointing. The primary science driver is the ability to track Galactic lensing events starting as soon as they are detected. This is a fairly loose specification. The astrometric effects of lensing have a time scale

of months to years, and the epoch of minimum approach can be set by the photometry, so a delay of 4 days is easily accommodated.

Question 4: What is the discovery potential?

SIM is primarily an astrometric mission, and the key observational parameter which SIM advances will be astrometric accuracy. SIM will extend the highest precision currently available (around 1 milliarcsec, from the Hipparcos mission) to $4\ \mu\text{as}$. This huge factor alone practically guarantees that SIM will have a strong capability for new discoveries. With the ability to integrate on faint objects, this accuracy extends down to around $V = 20$, encompassing a very wide range of astronomical objects for study.

Discovery of New Objects

Even though SIM operates from an input target catalog derived from existing observations, it has great potential for discovery. In searching for planets SIM will be essentially in a survey mode (albeit with a highly selected list to survey), and surveys are fertile ground for serendipity. The parameter space for planet detection encompasses virtually all the currently-known planets. Another opportunity for discovery comes from SIM's ability to respond to targets of opportunity — an obvious way to improve the odds of seeing the unexpected.

Planetary-Mass Companions to Nearby Stars. Target stars will be selected on the basis of currently understanding, and current questions, in planetary astronomy at the time of launch. But, the discovery space will have large uncharted areas. Ground-based radial velocity and astrometric instruments will probe the parameter space for planets more massive than Jupiter, especially with periods less than about 5 years.

SIM will explore a very large range of planet masses and orbit radii, down to a few Earth masses, and out to about 5-10 AU in radius. This is largely unexplored territory. And it will continue to be largely unexplored until SIM launches. There are theoretical expectations of what may be discovered, but these are not founded in a significant number of secure, bias-free, observations. Therefore, the scope for new and surprising discoveries is very large.

Gravitational Lensing Objects In Our Galaxy. SIM will unambiguously determine the mass of objects detected in ground-based microlensing surveys. The nature of these objects is still very uncertain, and masses will definitely be important in understanding them, whether or not they turn out to be a significant component of the total mass of the Galaxy.

Fundamental Astrophysics

SIM will have the ability to make major advances in many areas of stellar and Galactic astrophysics. Many of these will be derived from the fundamental physical quantities that will be measured by SIM. For instance, SIM will enable the luminosities of O stars to be determined accurately for the first time. We have estimates already, of course, but they are not sufficiently accurate to challenge the models which predict stellar luminosity as one of their principal outputs.

Close examination of other known classes of objects will certainly provide surprises. For example, distances to a sample of low metallicity subdwarfs will almost certainly show structure in their luminosities and kinematics not previously recognized, giving important clues to the

evolution of the Galaxy.

The characterization of the structure of the Galaxy on all scales in three dimensions will surely produce unexpected and challenging results. Major constraints on the extent and distribution of dark matter will be obtained. The transition from an uncertainty in the mass of the Milky Way of maybe 50% or more, to something more like 5% must certainly count as a discovery, whether the current value is confirmed or grossly altered.

Question 5: What are the technological hurdles to achieve success, with a status report and prognosis for solutions?

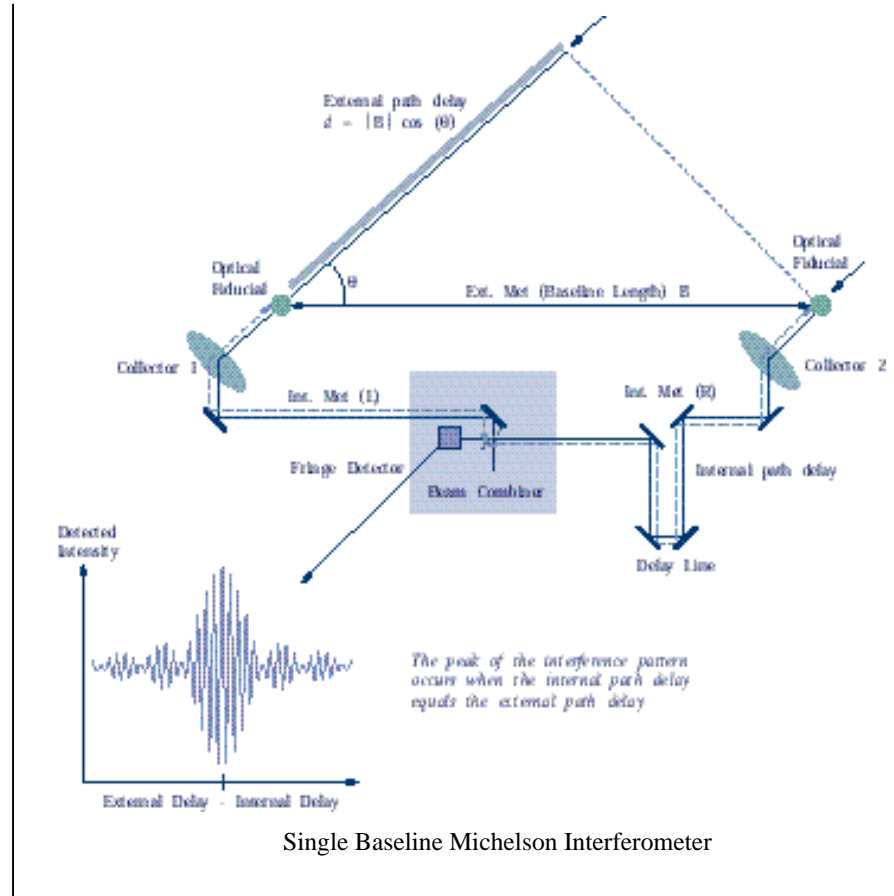
At the very top level, the major technological hurdles for SIM can be grouped into three categories:

- Ultra-precise measurement of optical path distances (to picometer levels)
- Maintaining a very quiet mechanical environment (limiting the jitter to nanometer levels)
- Integration and Testing of the interferometer system

Consider how a Michelson interferometer measures stellar positions. A single interferometer consists of: two collectors located at each end of the baseline, a delay line, and a beam combiner. Starlight is sent from each collector toward the beam combiner to form a white-light fringe. Because starlight is white, fringes only occur when the optical pathlength from the star through the two interferometer arms all the way to the combination point in the beam combiner are equal. To make this equalization possible, an optical delay line is added to one arm of the interferometer to adjust the optical path of that arm.

Once the delay line is set (via feedback of the white light fringe position on the beam combiner detector) to

a position where the paths are exactly equal, the angle to the star can be determined by measuring optical pathlengths in the interferometer. The interferometer baseline **B** is the vector formed by the vertices of the two fiducials located in front of the collector optics (see figure above). In



general, the path lengths through the two arms of the interferometer differ by an amount d . The angle between the baseline vector and the star is given simply by

$$= \cos^{-1}(d/|\mathbf{B}|)$$

where $|\mathbf{B}|$ is the length of the baseline vector. The distances d and $|\mathbf{B}|$ are measured by metrology gauges. The length of the baseline is measured by an “external” metrology gauge running between the left and right fiducials. The distance d is determined by using “internal” metrology gauges to measure the starlight path from the fiducials in each arm to the beam combination point.

Hence there are three fundamental observables used to make a stellar position measurement: (1) position of the white light fringe on the beam combiner detector; (2) readout of the internal metrology gauges; (3) readout of the external metrology gauge. The accuracy with which these measurements must be made scales directly with the astrometric requirements; i.e.

$$\text{Metrology gauge error} + \text{fringe detector error} = (\text{Baseline}) \times (\text{astrometry error})$$

Metrology Requirement. Note that astrometric measurements accurate to $1 \mu\text{as}$ made by a 10 meter interferometer imply metrology and fringe detection at the **50 picometer** level. The details, of course, are somewhat more complicated and involve the simultaneous operation of three Michelson interferometers, two devoted to tracking guide stars (which tie the instrument to inertial space) while the third tracks the science object. Furthermore, there are factors (e.g., the fact that the measurements are not absolute but relative, the application of averaging over time and multiple observations) that tend to mitigate somewhat the severity of the fringe and metrology measurement requirements. Nevertheless, the basic measurement technique is as outlined above and the precision required of the metrology gauges and fringe detection drives the **picometer sensing** technology development.

Stability Requirement. A second major class of technological challenge arises from the need to maintain a very quiet mechanical environment for the optics lest excessive vibrational jitter cause the detected fringes to blur and lose “visibility.” Once optical pathlength difference (OPD) motion begins to exceed **10 nanometers** ($\lambda/50$), the loss of fringe visibility becomes noticeable. The **nanometer stabilization** technologies are also driven by the SIM requirement to demonstrate a factor of 10,000 starlight nulling which demands even more stringent OPD jitter of **1 nanometer** RMS.

System I & T Challenge. The third technological hurdle that SIM needs to overcome can be captured by the phrase “putting it all together.” Optical interferometers consist of scores of independent but coordinated control systems that have to work flawlessly in concert. Although a number of ground-based observatories are in routine operation, interferometers have yet to be flown in space. Hence, **integration, test, and autonomous operation** deserves special developmental consideration for these unique instruments.

Technology Development Status

Technology development for SIM builds upon over a decade of precursor work done by the NASA micro-precision Control-Structure Interaction (CSI) program and a series of developmental ground-based interferometers. SIM technology development is led by the Jet

Propulsion Laboratory in Pasadena in collaboration with the two industry partners, Lockheed Martin Missiles and Space in Sunnyvale California and TRW Inc., Space and Electronic Group in Redondo Beach, California.

Our approach to technology development is that of rapid prototyping of critical hardware and software, followed by integration into ground-based technology testbeds. In these testbeds, critical interfaces are validated, system-level performance demonstrated, modeling techniques perfected, and integration and test procedures developed and verified. Flight experiments are undertaken only when the space environment is required.

Careful consideration has gone into the mix of component development, ground testbeds, and flight experiments. Questions that arise include:

- Can a technology be tested standalone on a test bench or is a testbed required?
- What testing needs to be done at full scale versus sub-scale?
- What testing has to be done in vacuum?
- Are real stars required or will pseudo stars do?
- Is zero-gravity required for any tests?
- What level of accuracy and precision is required for testing each technology?

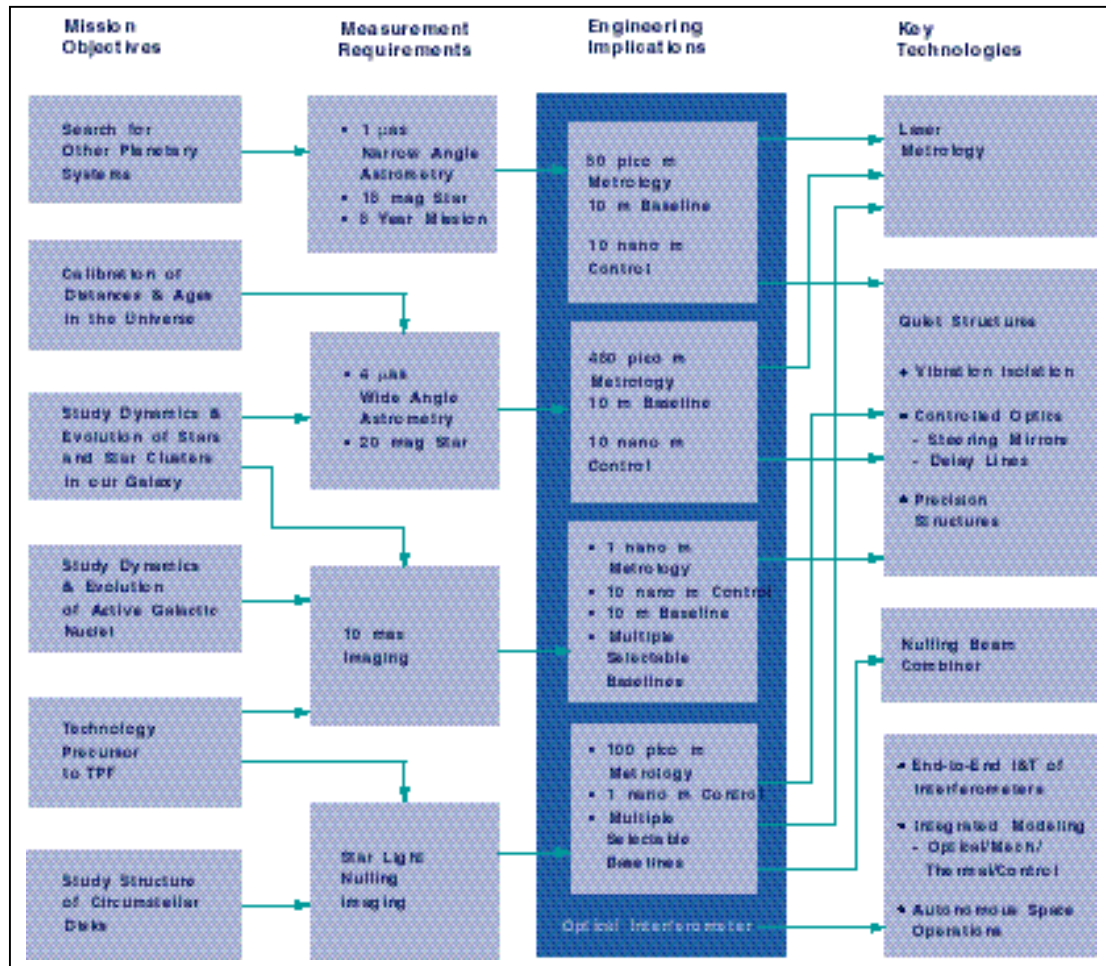
Cost effectiveness is a factor. The guiding principle is — accomplish the technical risk reduction that is necessary but do so at the minimum cost. Corollaries to this principle are: don't test in space what you can test on the ground; don't test in vacuum what you can test in air; don't use flight quality hardware if breadboards will do.

These considerations have led us to adopt a technology program that involves four major ground testbeds and two modest flight experiments. The flight experiments are both aimed at resolving the issue of “microdynamics” of precision deployed structures. The ground testbeds, discussed later in some detail, are the

- Microarcsecond Metrology (MAM) Testbed
- Micro-Precision Interferometer (MPI) Testbed
- Palomar Testbed Interferometer (PTI)
- SIM System Testbed (STB-3)

These testbeds aim at addressing major technological challenges at the system performance rather than piece part level. Roughly speaking, each testbed is matched against one of the three major technological challenges noted at the beginning of this section:

- MAM addresses the **picometer sensing** challenge
- MPI addresses the **nanometer stabilization** challenge
- PTI and STB-3 address the **integration, test, and autonomous operation** challenge



This flowchart relates SIM measurements requirement to mission objectives and, it highlights engineering implications and technology challenges in making those required measurements.

Modeling plays a critical role in conjunction with the system testbeds. It is through modeling that we are able to thoroughly understand the testbed data and interpret the implications for the SIM flight system. Demonstrated ability to accurately model particular phenomena observed in the testbeds lends credibility to analogous portions of flight system models upon which predictions of flight performance rest. If it were possible to test the full range of SIM technologies in a single testbed, then perhaps modeling would be rendered superfluous. As it is, modeling is the “glue” that bonds the disparate parts of the technology program together and makes them relevant to predicting flight system performance.

The summary status and prognosis for SIM technologies (including system level testing is given. This table should serve as a reference as the reader proceeds through the sequel which, in the service of brevity, can capture only the highlights of the technology program.

| | Technology | SIM Requirements | Status | Prognosis | |
|---|---|---|--|------------------------------------|---------------------|
| Nanometer Technologies | Controlled Optics | 2-m stroke optical delay lines | Brassboard 1-m ODL complete | beamwalk addressed by mid '00 | |
| | | 0.7 nm pathlength control | 1.3 nm control demonstrated | technology complete | |
| | | 150 nrad pointing control | within acknowledged state-of-the-art | | |
| | | 100 Hz closed loop bandwidth | ProtoCollector testbed in build | complete by end '99 | |
| | Vibration Isolation & Structural Quieting | 10 um beamwalk control over FOR | within acknowledged state-of -the-art | technology complete | |
| | | 30-40 dB 6-axis vibration isolation | | | |
| | Precision Deployment | structural vibration suppression (option) | active/passive options exist | complete by mid '01 | |
| | | 5-10 meter deployment | within acknowledged state-of-the-art | | |
| | | 3 cm initial deploy accuracy | SSTA testbed under design | | complete by mid '01 |
| | | 5 um long term stability | IPEX flown, grd test in process | | complete by end '00 |
| | Nanometer System Performance | sub-micron short term stability | demonstrated on MPI | technology complete | |
| | | 10 nm, 150 nrad jitter for astrometry | in process on MPI | complete by mid '01 | |
| 1 nm, 125 nrad jitter for nulling | | PTI dual star feed, STB-3 in build | | | |
| Guide star to science star ref transfer | | STB-3 in build | | | |
| Picometer Technologies | Laser Metrology | 50 pm 1-D gauge in 3-D experiment | 1 pm in 1-D expt (early '90's) 250 pm in 3-D expt, Kite planned | complete by mid '00 | |
| | | ~10-m distance | ~1-m distance, 10-m on Kite | complete by mid '00 | |
| | | Full aperture metrology (back-up) | initiated FAM components dev | evaluated by mid '00 | |
| | Astrometric Fringe Detection | 50 pm white light fringe tracking | in process on MAM testbed | complete by end '99 | |
| | Starlight Nulling | 10 ⁻⁴ achromatic null | 10 ⁻⁴ laser null, 10 ⁻³ achromatic null | complete by end '00 | |
| | Dimensionally Stable Optics | 30 pm / hr over 35 cm aperture | initiated TOM testbed | complete by mid '01 | |
| | | 1.6 pm / um of beamwalk | | | |
| | Picometer System Performance | 5 μas equivalent angular error | in process on MAM testbed | | |
| 250 pm met + white light error | | | | | |
| | Pathfind flight system perf test | | | | |
| Integration, Test, Ops | Realtime Interferometer Control Software | 65,000 lines of code | 30,000 lines of prototype code | prototype code complete by mid '01 | |
| | | tested in relevant environment | single baseline testing | 3 baseline testing by mid '01 | |
| | | Autonomous align, acquire, track | planned for STB-3 | complete by mid '01 | |
| | Techniques for Interferometer I&T | 3 baseline interferometer | STB-3 in process | complete by end '01 | |
| | | End-to-end nanometer testing | MPI under test, STB-3 in build | | complete by mid '01 |
| | | End-to-end picometer testing | MAM in build | | complete by mid '01 |
| | Integrated Modeling | Optics/structure/control/thermal | IMOS & MACOS mature tools | continuous improvement planned | |
| Models of all relevant testbeds | | MPI, TOM in process | complete by end '01 | | |

Legend:

FAM: Full Aperture Metrology

FOR: Field of Regard

IMOS: Integrated Modeling of Optical Systems

IPEX: Interferometer Program Experiment

MACOS: Modeling of Actively-Controlled Optical Systems

MAM: Microrcsecond Metrology Testbed

MPI: Micro-Precision Interferometer Testbed

ODL: Optical Delay Line

PTI: Palomar Testbed Interferometer

SSTA: Sub-Structure Test Article

STB-3: SIM System Testbed

TOM: Thermal Optomechanical

Nanometer Stabilization Technologies

The nanometer stabilization technologies have a direct lineage to the micro-precision CSI program, founded in 1988, and hence have achieved a fairly mature status. Work has been done at the component hardware level as well as through the integration of components and subassemblies into system level testbeds. Furthermore, this is an area in which a flight experiment was deemed necessary and two such experiments were successfully undertaken.

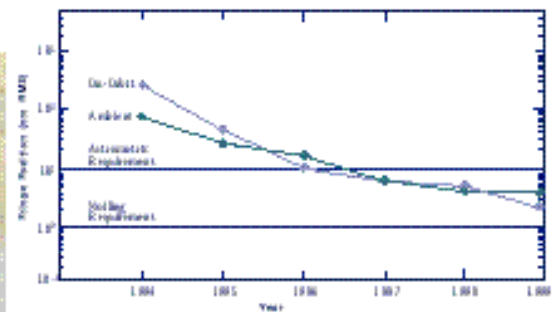
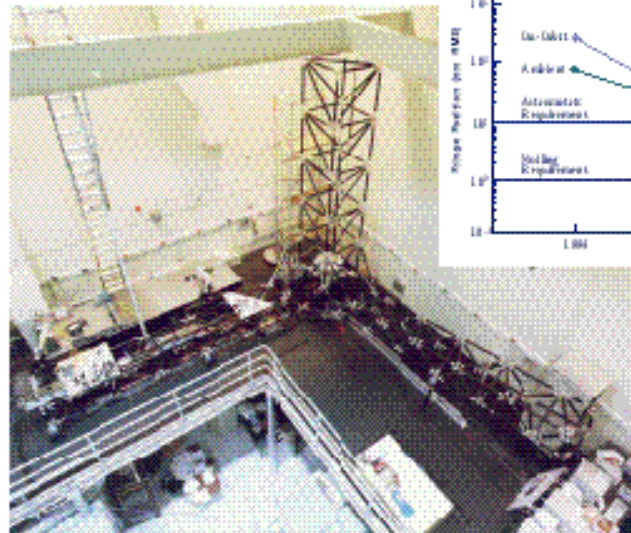
An example of a component developed within this segment of the program is the optical delay line. Although delay lines have been operational on ground-based interferometers for years, the ground versions are heavy, rely on gravity for seating the carriage on the rails, and do not require the 1 nanometer precision demanded by starlight nulling. By contrast, the brassboard delay line weighs in at about 10 kg, has been subjected to vibration and thermal tests at space flight levels, and has achieved 1.3 nanometers of control in benchtop tests.



Brassboard Optical Delay Line

System level nanometer testing has been underway since 1994 when the Micro-Precision Interferometer (MPI) Testbed became operational. MPI is a full single-baseline interferometer built on a flexible structure using breadboard hardware. The structure is an aluminum truss, 7 x 6.8 x 5.5 meters in size. With optics and control systems attached, the total weight is about 600kg.

The principal objectives of MPI are to demonstrate vibration-attenuation technologies and validate our modeling techniques in the nanometer regime. MPI was completed in summer 1994, when “first fringes” were acquired. Two metrics have been tracked over time to monitor testbed progress: (1) pseudo-star fringe tracking stability in the presence of the laboratory ambient



Micro-precision Interferometer (MPI) Testbed with performance over time (inset)

vibration environment, and (2) fringe stability versus emulated spacecraft reaction wheel disturbances, which are expected to be the dominant on-orbit disturbance source. By both of these metrics, **the astrometric stabilization requirement of 10 nanometers is well in hand and we are closing in on the goal of 1 nanometer for nulling.**

The two flight experiments undertaken by the SIM technology development effort were aimed at addressing nanometer stabilization issues associated with the microdynamics of precision deployable structures. The rationale for going to space is that it is not possible to conclusively prove through ground tests alone that structures which contain hinges and latches and joints, and hence have the potential to exhibit stick-slip behavior, will perform in zero-g in as linear a manner as they perform in 1-g.

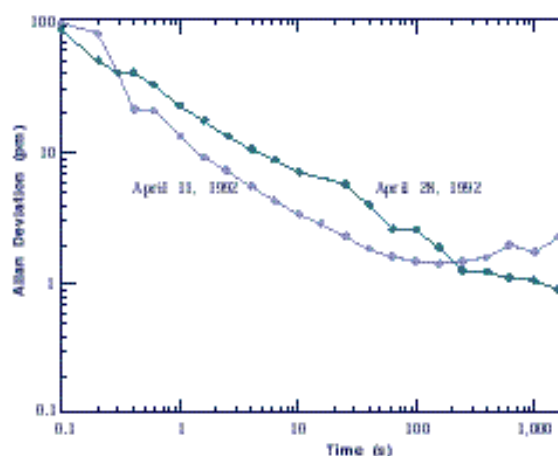
The flight experiments were flown under the banner Interferometry Program Experiment (IPEX 1&2). IPEX-1 was hosted on German Space Agency's Astro-SPAS free flying platform, which sortied from space shuttle bay during a mission in December 1996. IPEX-1 gathered 12 channels of micro-g acceleration data to characterize the Astro-SPAS mechanical disturbance environment. The successor experiment, IPEX-2, was flown in August 1997, a scant eight months after IPEX-1. IPEX-2, also flown on Astro-SPAS, consisted of an instrumented portion of a representative deployable structure provided by ABLE Engineering Corp. Over 60 channels of accelerometer, load cell, and temperature data were taken during various orbital thermal conditions, including sunshade transitions and long-duration hot and cold soaks. The preliminary conclusion of these two flight experiments is that deployable structures that are engineered to eliminate backlash in joints and are placed in thermally benign orbits, such as an Earth escape orbit like SIM's, will exhibit sufficiently low levels of microdynamics to support optical interferometry. The ultimate intent is to combine the flight data with ground test measurements to develop empirically validated analytical models of microdynamic phenomena for use by the flight team.

Picometer Sensing Technologies

JPL has been working on the building blocks of picometer sensing technologies. Significant progress has been made at the component and subsystem level: laser gauges, astrometric and nulling beam combiners. However, work remains to be done in the build-up of the components into system level testbeds that demonstrate the ability to make microarcsecond angular measurements.

Development of the heterodyne laser gauges for SIM involves the combination of several components (i.e., laser, stabilizer, frequency shifter, frequency modulator, fiber feed, beam launcher, corner cubes) into a system capable of making measurements with 50 picometers resolution over meters of separation distance. The fundamental feasibility of building such gauges was demonstrated several years ago when breadboard gauges were tested in both null and relative gauge configurations.

The current effort concentrates on the careful build-up of the heterodyne gauge in a manner that is traceable to the thermal and mechanical environment in which the gauge must work on



Picometer Performance of the Heterodyne Null Gauge
Shown as Allan Deviation vs. Time

orbit. Some of the key components have already reached brassboard status, including the laser and beam launcher.

SIM will require the laser metrology system to synthesize the 3-dimensional motion of the corner cube fiducials from a set of 1-dimensional single gauge readings. This requirement demands that individual gauges interrogate a common corner cube over incidence angles that vary by up to 15 degrees as different stars are observed. The performance of the gauges in this time varying 3-D setting is as yet unproven. Hence, we plan by the end of 1999 to demonstrate this capability in a six-gauge experiment, dubbed the “Kite” experiment due to its layout. An earlier pathfinding 3-D metrology experiment was important for helping us determine the appropriate configuration for Kite. The early experiment involved the simultaneous use of five gauges to track the position of a single corner cube. The redundancy of the measurement (only 3 gauges are required to deduce the corner cube’s x,y,z motion) allowed us to derive the gauge performance via consistency comparisons. Results were good – individual gauge performance of about 250 picometers – but not good enough to meet the 50 pm objective. The experimental error is considered attributable to the fact that the positions of the five gauges relative to one another was not directly monitored but assumed to be sufficiently stable (they were mounted on a meter square invar plate). It is this latter assumption on mounting stability that is suspect. This error source will be eliminated in the upcoming Kite experiment.

The picometer sensing technologies are so central to the fundamental measurements that will be made by SIM that it is considered insufficient to prove the constituent pieces alone, without combining these pieces in an end-to-end test. The Microarcsecond Metrology Testbed (MAM) will demonstrate that the picometer white light and laser light components can be configured in an interferometer to measure the position of a point source to the microarcsecond level. This will be done at one-fifth scale in a 3 by 13 meter vacuum chamber. MAM uses a 1.8m-baseline interferometer to observe an artificial star. The positions of the star and the interferometer are monitored by an external metrology system during the experiment.



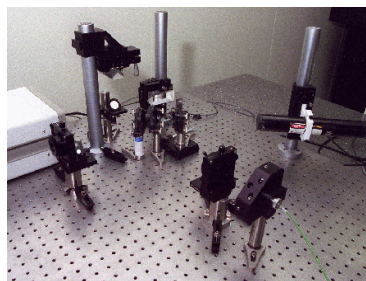
Microarcsecond Metrology Testbed (MAM)

The MAM interferometer includes all the functionality of the flight system in a reduced-scale and reduced-dimensionality experiment, enabling MAM to pathfind the ground performance testing methodology for the flight instrument. The MAM optics, metrology system, and artificial star are placed in a vibration-isolated, thermally stabilized vacuum chamber. This eliminates index of refraction fluctuations in air to achieve the goal of 50-picometer optical path measurement accuracy.

The MAM vacuum chamber is in place and ready for testing to begin. Initial MAM operation is planned for mid 1999 when white light fringe tracking tests will be conducted. These will be followed by a single-baseline, narrow-angle experiment where the artificial star will be moved over a 20-arcsecond (1-millimeter) range. The position of the star will be monitored by both the white-light interferometer and the external metrology system, providing a consistency check. The next stage of experiment will be to increase the field of view, eventually reaching 5 degrees.

Later, heaters and vibration transducers will be added to key optical components to study the effects on calibration and operation of the interferometer.

Starlight Nulling. Both astrometric and nulling beam combiners have been developed since they are considered key components. A brassboard astrometric combiner was built to investigate flight related thermal and mechanical issues. The nulling beam combiner is a less mature technology and is currently at the breadboard (or tabletop) stage. The challenge of building an instrument capable of achieving a factor of 10,000 destructive interference across a broad waveband (~ 20 percent) is considered severe; so much so that two different techniques are being pursued in parallel, one at JPL and the other at the University of Arizona. Prior to December 1998, each effort had achieved roughly a factor of 1,000 null on laser light and a factor of 20-40 on white light. In December 1998, the JPL effort achieved a factor of 25,000 null on a laser diode source (~ 0.5 percent bandpass). Currently, we are pushing to duplicate this result on broadband light and thereby establish the feasibility of SIM nulling.



Tabletop Breadboard Nulling Beam Combiner (top) and Brassboard Astrometric Beam Combiner (bottom)

Interferometer Integration, Test, and Operation.

The techniques for integrating, testing, and operating an optical interferometer have been well established for ground based observatories. The challenge is to extend and modify these techniques for the special requirements of space flight. Nevertheless, ground based stellar interferometers are invaluable testbeds for space-based systems, not only from a hardware perspective, but also with a view toward operations and scientific productivity. Members of the JPL team have built and operated a series of ground interferometers over a period of nearly 20 years. These interferometers have pioneered advances in interferometer architecture, algorithms, performance, automation, and scientific productivity that are directly applicable to SIM.

The Mark I through Mark III interferometers were built and operated on Mt. Wilson in Southern California. They were technological forerunners of the Palomar Testbed Interferometer (PTI), funded by NASA to demonstrate the technology for ultra-precise narrow-angle astrometry. Development of PTI began in December 1992. The site at Palomar Mountain was available for occupancy in May 1995 and first fringes were obtained three months later, in July 1995. The instrument recently attained its performance goal of sub-50-microarcsecond, narrow-angle astrometry, at least over single observation times on the order of hours. Testing of multi-night astrometric measurement stability is currently under way.

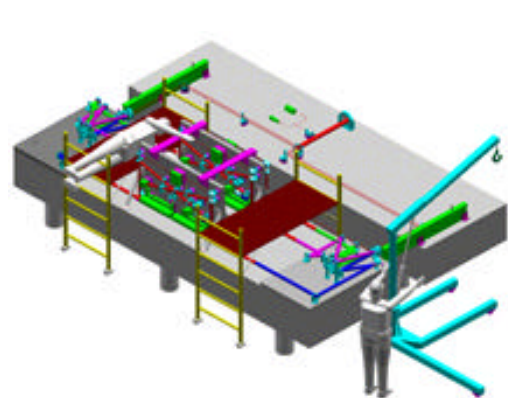


Palomar Testbed Interferometer

PTI was built in a highly modular manner, both with respect to the optical system and the computer control system. Modularity enabled the testing of subsystems in the lab and on the roof of our lab at JPL, so that final systems integration on the mountain took less than three months to obtain first fringes. The SIM flight team plans a similar rapid system integration. PTI, while borrowing extensively from the Mark III, incorporated all new software. The modularity and testability of the software architecture allowed a rapid development cycle. The architecture is also somewhat autonomous and can support some remote operations from JPL.

The PTI team developed more than 100,000 lines of realtime interferometer control software. This software has been inherited by the SIM team and will form the basis of the SIM instrument flight software. As part of the technology development program, this software is being extensively rebuilt and adapted to the requirements of operating a three baseline interferometer like SIM as well as the special requirements of space flight. It is projected that SIM, through a streamlining of the PTI code, will require a total of about 65,000 lines of instrument flight software. Almost half this amount has been prototyped to date. The proving ground for this prototype software will be the SIM System Testbed (STB-3).

STB-3, the "3" stands for 3 baselines, is being built in the image of SIM to demonstrate readiness to handle integration and test of the flight instrument. STB-3 will build upon the PTI experience, bridging the gap between a single baseline ground observatory and a multiple baseline system built on a flexible structure and operating beyond the reach of helping hands. In addition to capturing the interactions (both intentional and unintentional) between multiple baselines, STB-3 will demonstrate numerous other functions that must be accomplished by a flight interferometer: initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, retarget, and reacquisition. In many ways STB-3 will be the culmination of the technology development effort. It will be transferred to the flight instrument development team once SIM begins its implementation phase where it will see use as an on-going software development testbed and as a learning tool for integration and test of the flight system. STB-3 is currently under construction with initial 3 baseline operation expected by late 1999 or early 2000.



SIM System Testbed (STB-3)

Summary and Prognosis

SIM is technically challenging. There is no way to avoid that conclusion. The requirements for nanometer stabilization and the integration of multiple interactive computer controlled systems are difficult to meet. The demands of picometer sensing are beyond the current state-of-the-art, even for laboratory systems.

Nevertheless, years of development have resulted in sustained progress. The goal of nanometer stability is practically in hand. Starlight nulling to better than a part in 10,000 looks attainable. Complex ground based interferometer observatories have been built and are operating on a routine basis. Laser gauges have been built that demonstrate the feasibility of making picometer regime relative distance measurements.

The prognosis for success is good. Progress will not be monotonic. There will be setbacks. However, there will also be breakthroughs where we succeed more quickly and with better performance than called for in our plans.

The major hurdles that remain entail putting the pieces together and proving that they play as systems. Metrology gauges have to be tested in 3-D and then configured with a white light interferometer to demonstrate microarcsecond angular measurements. A multiple baseline interferometer that functions like SIM needs to be built to prove that baseline-to-baseline interactions and complexities are understood. These efforts are planned and in fact already well underway. With our exceptional team and committed NASA resources, we expect to complete these critical demonstrations over the next two years and place the project in position to proceed beyond its Non-Advocate Review (NAR) into a successful implementation phase.

Question 6: What is the future potential of the technology developed for this mission? What is the expected growth path?

By virtue of the fact that SIM will be the first of a new breed of space optical system its technology is bound to have a profound effect on missions that follow. SIM will pioneer the development of dilute apertures for space science. This technique allows the instrument designer to separate the two fundamental parameters of an optical system: sensitivity (viz., light-collecting power) and resolution. Heretofore, in a world defined by filled aperture telescopes, these parameters have been inextricably tied together by their common dependence on the diameter of the aperture. By breaking free of this restriction, dilute apertures will become prevalent in the 21st century, taking on forms that cannot be completely anticipated today but tailored to the scientific quest of the moment.

Today it appears likely that the Terrestrial Planet Finder (TPF) will be the first heir to the technological legacy of SIM. Optimized for synthesis imaging of extra-solar planetary systems via the technique of nulling interferometry, TPF will be the direct beneficiary of practically every technology in the SIM chest. In fact the SIM objectives of demonstrating dilute aperture synthesis imaging and starlight nulling are direct derivatives of its role as a technological precursor to TPF.

SIM nulling will pathfind TPF nulling in three fundamental ways:

1. Development of a nulling beam combiner capable of a deep achromatic starlight null
2. Development of optical stabilization technologies capable of producing 1 nm OPD at the nulling beam combiner (this level of stability is necessary to meet both SIM's 10^{-4} nulling requirement at 1 μm as well as TPF's 10^{-6} nulling requirement at 10 μm)
3. Development of single-mode fiber approach to do wavefront "clean-up" to $\lambda/1000$ via spatial filtering of the interferometrically combined wavefront

Besides benefiting TPF, several of the technologies being developed for SIM will have direct application to most imaginable variants of dilute aperture optical systems. All will require nanometer class stabilization of distributed optical elements and a high degree of coordination among hierarchical realtime control systems. Hence the following technologies will find broad application:

- Controlled optics (delay lines and steering mirrors)
- Vibration isolation
- Structural quieting
- Microdynamically stable precision deployable structures
- Autonomous realtime interferometer control architecture and software
- Integrated modeling across the disciplines of structures, control, optics, thermal
- Techniques for integrating and testing interferometers

Although the picometer sensing technologies will not be required to operate at full precision by some dilute aperture systems, the following technologies will also be required by most of these systems with relaxed tolerance specifications:

- Laser metrology
- Starlight fringe tracking
- Starlight nulling beam combination
- Millikelvin controlled dimensionally stable optics

Additionally, some future filled-aperture systems will apply SIM technology, especially as they move to segmented optics configurations. NGST, for example, is baselining vibration isolation as well as fast steering optics for its current designs and is using the same integrated modeling tools (IMOS and MACOS) developed for SIM. NGST also has an interest in microdynamics and is holding open (as a back-up) the possibility of using laser metrology to help maintain its optical figure over time.

Predicting the future path that technology development will take is by its nature fraught with uncertainty. Some reasonable conjectures can be made, however. In some cases the growth path to future systems will be simply application of SIM developed capability without modification. For future systems operating in the infrared (e.g., TPF) much of the technology will need to be adapted to the requirement of operation at cold temperatures (30K—100K). This will place greater stress on the nanometer technologies which are dominated by mechanisms and motion control devices. Some changes to the picometer systems should also be anticipated. Another avenue for technological growth will be prompted by the increase in interferometric baseline length. As baselines exceed ten's of meters and ultimately ten's of kilometers issues like beam divergence begin to dominate considerations of metrology systems and starlight beam transfer. New approaches taking into account significant diffraction effects will need to be developed.

Of course, these are only the technological developments that we can anticipate. There is bound to be a large class of SIM technology whose application will surprise us. Conversely, next generation systems will certainly require additional developments, currently unimagined, which will take us beyond the set of arrows in the SIM quiver.

References

“SIM—Taking the Measure of the Universe” sent to the panel earlier
SIM Web Page — <http://sim.jpl.nasa.gov>
Origins Web Page — <http://origins.jpl.nasa.gov>

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